LA-UR- 04-1897

Approved for public release;
distribution is unlimited.

Title: Los Alamos activities on HE detection using nuclear resonance absorption technique

Author(s): Thomas J. T. Kwan

Submitted to: WSSX Technical Information Exchange Meeting
Snezhinsk, Russia

Los Alamos
NATIONAL LABORATORY

Los Alamos Activities on HE Detection Using Nuclear Resonance Absorption Technique*

Thomas J. T. Kwan

The feasibility of detecting high explosives through the nitrogen nuclear resonance absorption of the 9.17-MeV gammas produced by carbon-13 nuclei via radiative capture of 1.75-MeV protons was demonstrated almost ten years ago at Los Alamos National Laboratory. The practical application of this technique requires advances in several enabling technologies. The most important issue is the generation of a high quality proton beam with appreciable current (>10 mA) to produce the minimum number of resonance gammas to achieve the required throughput in baggage/cargo interrogation. We have performed a parameter study of the use of a compact cyclotron as an injector to a proton storage ring with energy recovery and electron cooling capability to maximize the intensity of the proton beam. We have also started our computational effort in applying MCNPX in our newly developed radiographic chain model to model the radiographic imaging process. Details of our studies will be presented.

* In collaboration with Tai-Sen Wang and Richard Morgado

Los Alamos Activities on HE Detection Using Nuclear Resonance Absorption Technique*

Thomas J. T. Kwan
Los Alamos National Laboratory
Los Alamos, NM
U.S.A.

U.S. and Russian Technical Interchange Meeting
Warhead Safety and Security Exchange (WSSX)
April 19 – 23, Snezhinsk, Russia

* In collaboration with Tai-Sen F. Wang, and Richard Morgado

NNSA

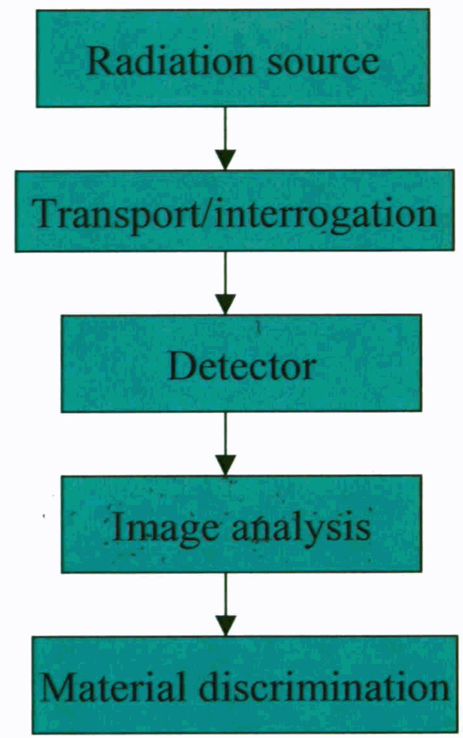
Los Alamos
NATIONAL LABORATORY

Current status of probing radiation technology for detection of bulk explosives

- Many detection principles are well studied and understood
- Current systems use x-ray technology which are not material specific and therefore have high false alarm rate.
- Nuclear techniques in conjunction with tomography can determine atomic density (mol/cc) of elements due to their distinct nuclear reactions with radiation.
- Development of enabling technologies is crucial to achieve system reliability, accuracy, and throughput rate for practical applications.

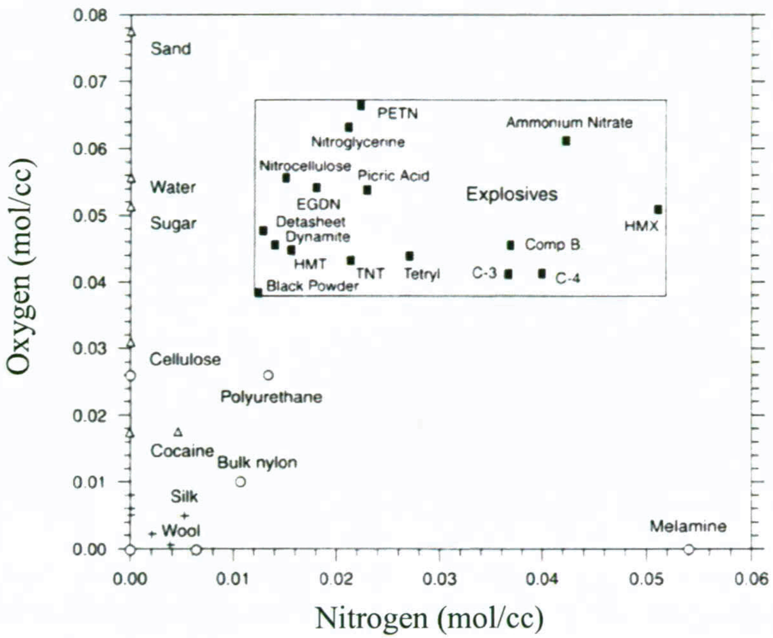
A detection system for bulk explosives consists of a diverse set of enabling technologies

- Probing radiation – γ-rays or neutrons
  - Charged particle accelerators
  - Neutron generators
- Charged particle transport and target interaction
- Radiation detectors - data collection
  - High efficiency and resolution detector technology
- Image analysis - material discrimination
  - 3-D reconstruction
  - Atomic density determination

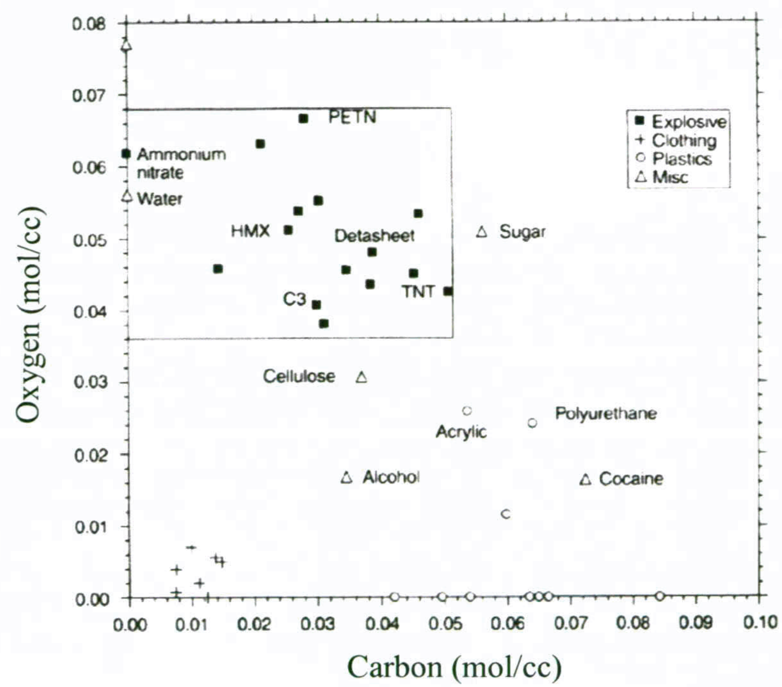


In order to meet a minimum throughput rate with an acceptable false alarm rate, a detection system will likely deploy an integration of complementary technologies such as γ-ray nuclear resonant absorption, fast neutron analysis, and high-resolution x-ray imaging.

Explosives have strong correlation among nitrogen, oxygen, and carbon molar concentrations



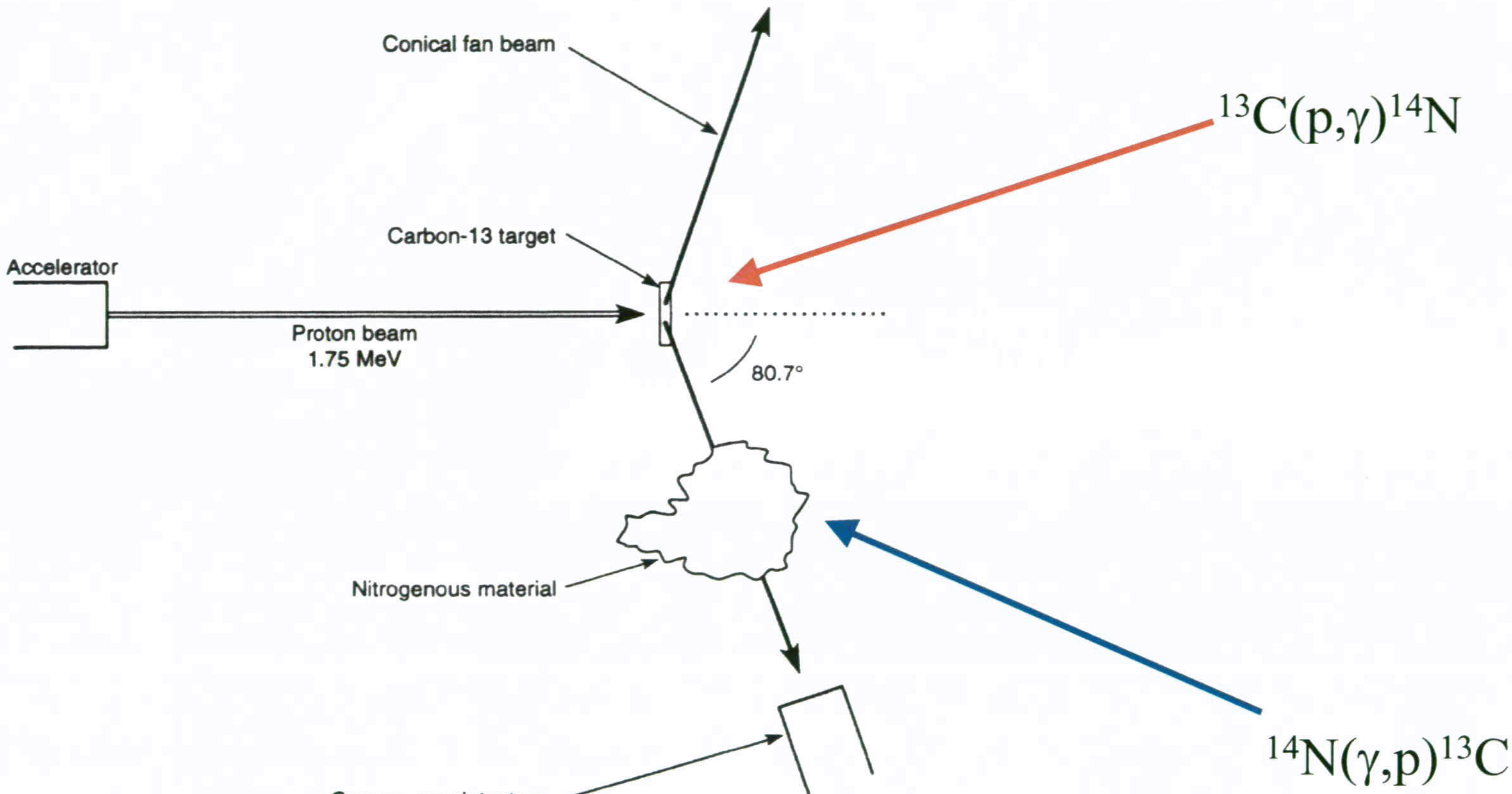
Jehuda Yinon, *Forensic and Environmental Detection of Explosives*, John Wiley & Sons, Inc.



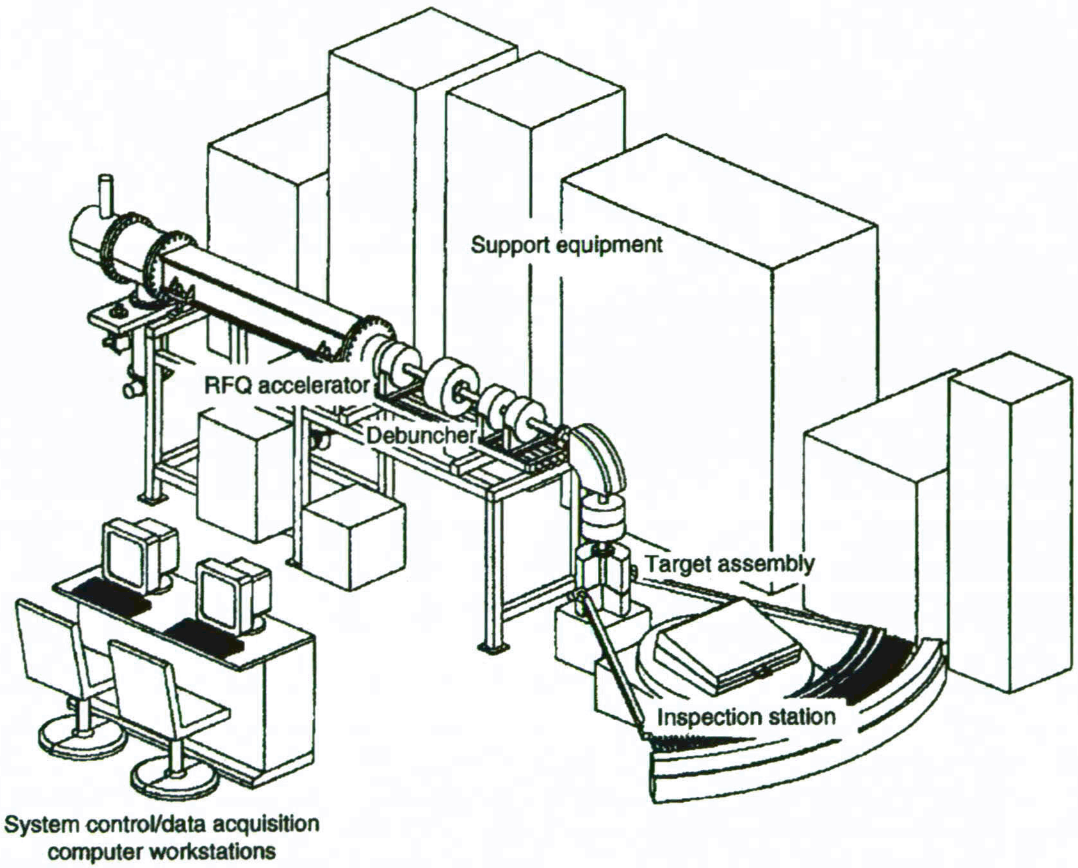
NNSA

Los Alamos NATIONAL LABORATORY

γ-ray Nuclear Resonance Absorption (NRA)



Explosives Detection System based on Nuclear Resonance Absorption in Nitrogen LANL Tomographic Imaging Prototype - 1993



- 1.75-MeV protons from Radio-frequency Quadrupole (RFQ) accelerator
- 64-detector bismuth germanate (BGO) scintillator detector array
- tomographically scanned luggage yields a 3-D image of nitrogen density in explosives
- real explosives in FAA suitcases

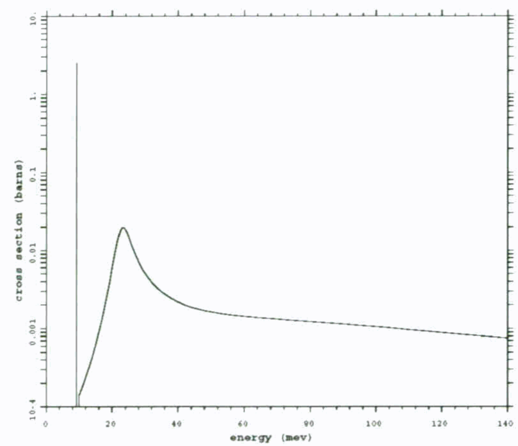
Critical technologies for the NRA method

- Proton accelerator – high current to maximize resonant γ-production
  - High current (1 mA or better)
  - Low energy spread (1.5 keV or better required)
- Target design
  - Optimization of ^{13}C thickness for maximum resonant γ-production
  - Mitigation of target vaporization (cooling)
- Detector optimization and development
  - Efficiency
  - Energy resolution
  - Spatial resolution
- Tomographic system simulation
  - 3-D reconstruction from synthetic radiographs (fan beam)
  - System optimization (target thickness, detector response, geometry)

Simulation of NRA method needs new implementations in MCNPX Monte Carlo code

Simulation Sequence:

1. 1.75 MeV protons impact C^{13} and emit 9.17 MeV gamma
   - Nuclear data evaluation is needed for the $C^{13}(p,\gamma)$ interaction
   - Without a proper evaluation, we must develop a model for gamma emission.
2. Develop angle biasing to increase statistics around the 80.8° bin relative to the incoming C^{13} beam
3. The 9.17 gamma is absorbed in the target nitrogen.
   - The gamma absorption cross section for N14 exists (see figure).
   - Determine if the secondary emission in the current evaluation is appropriate in order to evaluate the problem background.
4. Adapt the energy stepsize in MCNPX so that the very narrow resonance is adequately sampled.



Absorption cross section
For gammas in N^{14}

An NRA detection system with nominal parameters requires a proton beam with 1.6×10^{13} protons per pulse

- 4 bags/group for simultaneous interrogation
- 1 bag/quadrant on a circular interrogation platform
- Interrogation at 4 vertical positions with 4 rotations/vertical position
- Total interrogation time/group $\approx$ 16 seconds
- 256 detector units in total
- 400 γ count/detector unit
- Resonant gamma yield $\approx 0.63 \times10^{-8}$ γ/proton
- Assuming 8 seconds for loading and unloading time, interrogation time/bag $\approx$ 6 s
- Need ~ 1.6×10^{13} protons to produce 1×10^{5} resonant gammas
- Proton beam quality: $\varepsilon_0 \approx 15\pi$mm$\times$mrad (unnormalized), $\Delta E/E \approx 1\times10^{-3}$

Estimate of the maximum number of protons in a storage ring

- A crude scaling relation from incoherent tune shift formula,

$$\frac{(N_p)_1}{(N_p)_2} \approx \frac{\gamma_1^3 \beta_1^2 \varepsilon_1 / G_1}{\gamma_2^3 \beta_2^2 \varepsilon_2 / G_2},$$

$N_p =$ maximum number of protons in the ring,

$\gamma = (1-\beta^2)^{-1/2}$ $\qquad$ $\beta = v/c$

$v =$ axial speed of protons $\qquad$ $c =$ speed of light

$G \sim$ depends on the ring lattice design,
use $G \approx 1$ for approximation.

- For the NRA ring, $E_1 = 1.75$ MeV and $\varepsilon_1 = \varepsilon_0 \approx 15\pi$mm·mrad.

Estimate of the maximum number of protons in a storage ring (cont.)

- Scale from the Novosibirsk INP ring

  $E_2 = 1$ MeV, $(N_p)_2 \approx 3\times10^{11}$, and assuming $\varepsilon_1 = \varepsilon_2$,

  we have $(N_p)_1 \approx 5.3 \times10^{11}$ for the NRA rings.

- Scale from LANL PSR

  $E_2 = 800$ MeV, $(N_p)_2 \approx 5.5\times10^{13}$, and $\varepsilon_2 = 10\pi$mm·mrad,

  we have $(N_p)_1 \approx 7 \times10^{10}$ for the NRA rings.

- For the small $\Delta E/E$ of the NRA rings, reasonable to assume $N_p \approx 1\times10^{11}$.

Emittance growth due to target-foil scattering

$$\varepsilon = \varepsilon_0 + \delta\varepsilon \,, \qquad\qquad \delta\varepsilon \approx \pi\beta_0\, nt\sigma_c\langle(\delta y')^2\rangle \,,$$

β_0 = lattice beta function at target foil $\approx$ 1.67 m

$nt \approx 7.5\times10^{22}$ atom/m^2 for 150 μg/cm^2 carbon foil

$\sigma_c\langle(\delta y')^2\rangle \approx 1.9\times10^{-28}$ (m•rad)^2/atom

- We estimate that $\delta\varepsilon \approx 23.8\pi$mm×mrad $\approx 1.6\ \varepsilon_0$ per pass.
- We need about one cooling time to cool the proton beam from $2.6\varepsilon_0$ down to ε_0.

NNSA

Los Alamos
NATIONAL LABORATORY

Electron cooling time

- $\varepsilon \approx \varepsilon_0 \exp(-t/\tau)$

  τ = cooling time $\approx \gamma^2 \langle \mathbf{v}^2 \rangle^{3/2} / (6\pi \eta_c n_e L r_e r_p c^4)$
  $\mathbf{v}$ = proton velocity in the beam frame
  η_c = fraction of ring for cooling
  n_e = electron density
  L = Coulomb logarithm ≈ 10
  r_e, r_p = classical electron and proton radii

- Typical order of magnitude $\approx$ 1s for low energy proton beams.
- Assuming $\tau \approx$ 1s, one proton pulse per second from a ring is feasible.

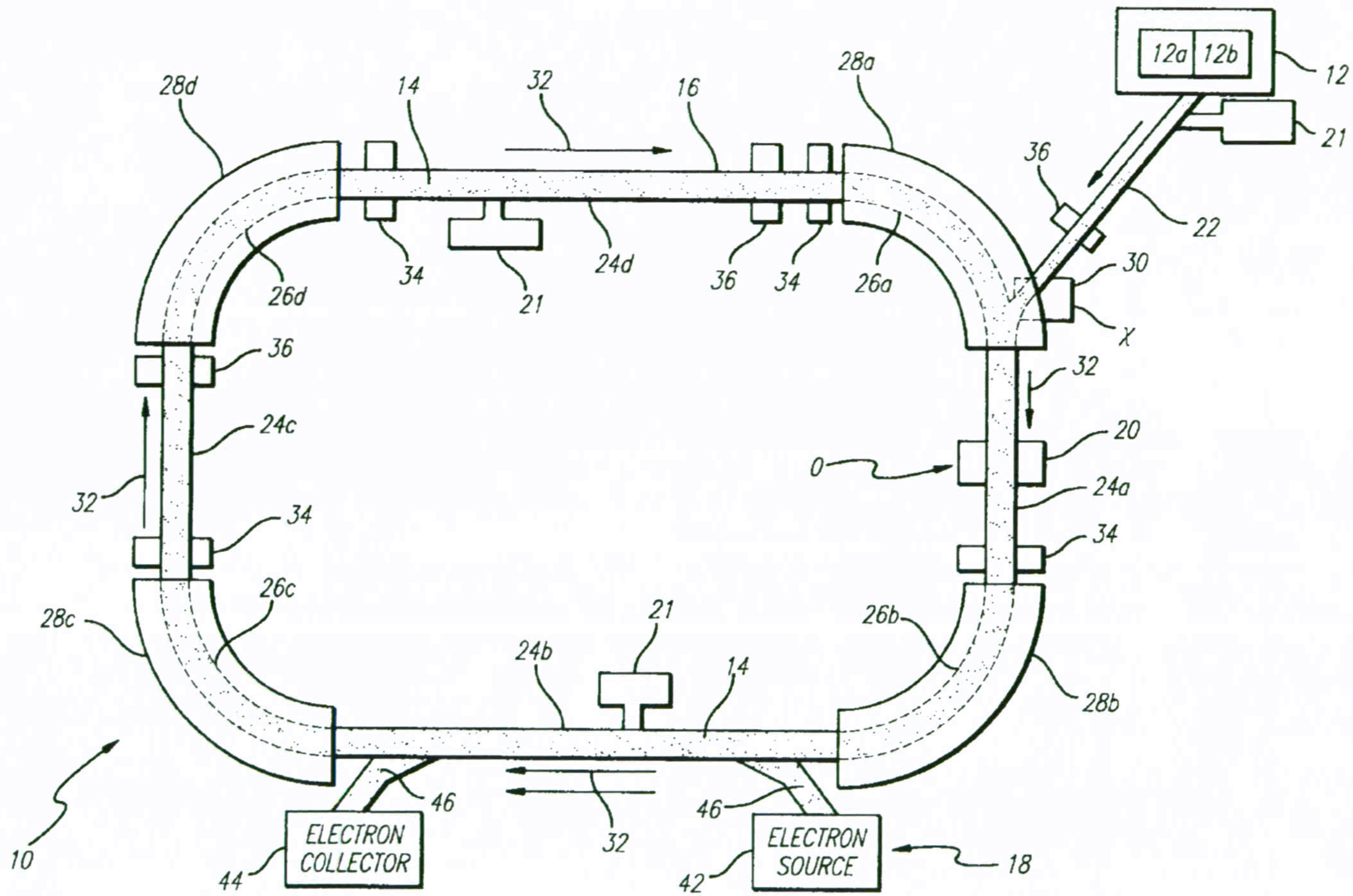
Nominal ring parameters

square or rectangular ring, 1-m-long cooling section, 1s cooling time, one 6-MHz rf cavity, 1.75 MeV cyclotron injector

$E = 1.75$ MeV
$C = 12$ m
$\nu \approx 0.71, 0.23$
$\beta_{max} \approx 15$ m
$\beta_{min} \approx 2$ m
$Y_{max} \approx 1.5$ cm
$Y_{min} \approx 0.55$ cm
$T \approx 0.667\ \mu s$

$f_{rev} \approx 1.5$ MHz
$N_p \approx 1\times10^{11}$
$I_{av} \approx 24$ mA
$I_{peak} \approx 0.5$A (?)
$r_{pipe} \approx 6.3$ cm
$V_{rf} \approx 2$kV (?)
$h = 4$

SAIC storage ring conceptual design



SAIC storage ring parameters

2-periods rectangular ring, 1.33-m-long cooling section,

$E_p = 1.75$ MeV
$C = 11.1$ m
$N_p \approx 1\times10^{12}$
$I_p \approx 250$ mA
$T \approx 0.6$ μs
$E_e = 951$ eV
$I_e \approx 1$ A

$\tau \approx 48$ ns
$a = x = 17$ mm
$\Delta E_p = 3.5$ keV @ injection
$\varepsilon_{nx} \approx 0.5\pi$mm×mrad @ injection
$\delta E_p = 210$ eV (growth @ target)
$\Delta\varepsilon_{nx} \approx 0.0854\pi$mm×mrad
(growth @ target)

Problems with the SAIC ring design

- We estimate a cooling time (τ) of 30ms instead of 48ns as claimed.
- Emittance growth due to interaction with target is expected to accumulate from turn to turn.
- Both the usable proton beam current and the resonance gammas will be orders of magnitude smaller than those evaluated before.
- Beam stability at $N_p \approx 10^{12}$ is unclear.

Electron cooling time and number of protons in the storage ring are critical issues for NRA applications

Number of storage rings $\propto (1/N_p)(1/\tau)$

Examples:

- For $\tau \approx 0.1$s and $N_p \approx 2\times10^{12}$, 1 ring is needed
- For $\tau \approx 0.1$s and $N_p \approx 5\times10^{11}$, 3 rings are needed
- For $\tau \approx 0.5$s and $N_p \approx 2\times10^{12}$, 4 rings are needed
- For $\tau \approx 0.5$s and $N_p \approx 5\times10^{11}$, 16 rings are needed